# ENERGETIC ALPS FROM DECAYING DARK MATTER

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based on
arXiv: 1806.08569
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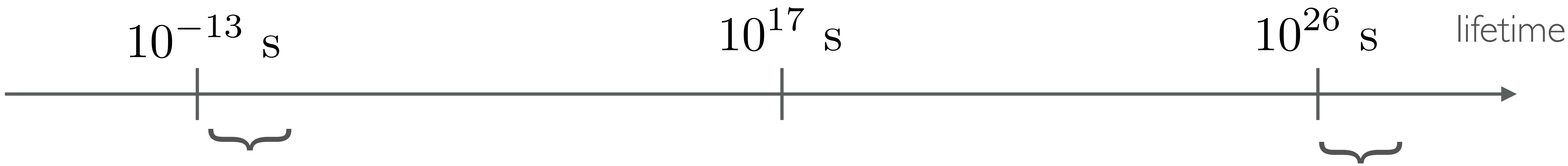
May 22, 2019

# LONG-LIVED PARTICLE




Long-Lived Particles

$c\tau \gtrsim 0.01 \text{ mm}$

signals in the lab

(meta)-Stable Particles

$\tau \gtrsim 10^{26} \text{ s}$

DM; (in)direct detections

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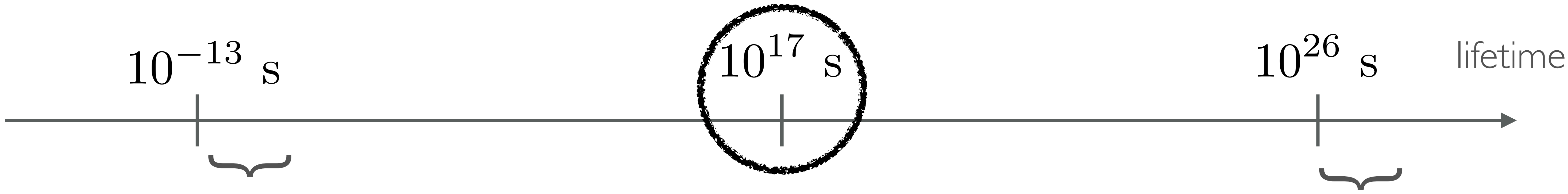


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Super-Long-Lived Particles: Decaying Dark Matter

$\tau \sim \tau_U \sim 10^{17}$ s

- Impact on small-scale structure O(10) kpc
- signal on the sky: e.g. gamma-ray

# OUTLINE

1. Introduction
2. Late Decaying Dark Matter
3. ALPino to ALP
4. Conclusion

# SMALL SCALE PROBLEMS?

- CDM works well at scale >100 kpc.
- Issues arise at scale O(10) kpc or smaller
  - missing satellite problem
  - too-big-to-fail problem
  - core-cusp problem
  - ... and more
- Baryon may solve the problem
- Debate is not conclusive:

  in this talk, these are motivation to consider an alternative non-CDM model.

# POPULAR MODELS

- Warm Dark Matter: $m_{\mathrm{WDM}} \sim \mathrm{keV}$

  freestreaming of DM suppresses small scales.

- Fuzzy Dark Matter: $m_{\mathrm{FDM}} \sim 10^{-22}\ \mathrm{eV}$

  Long de-Broglie wavelength of DM suppresses small scales.

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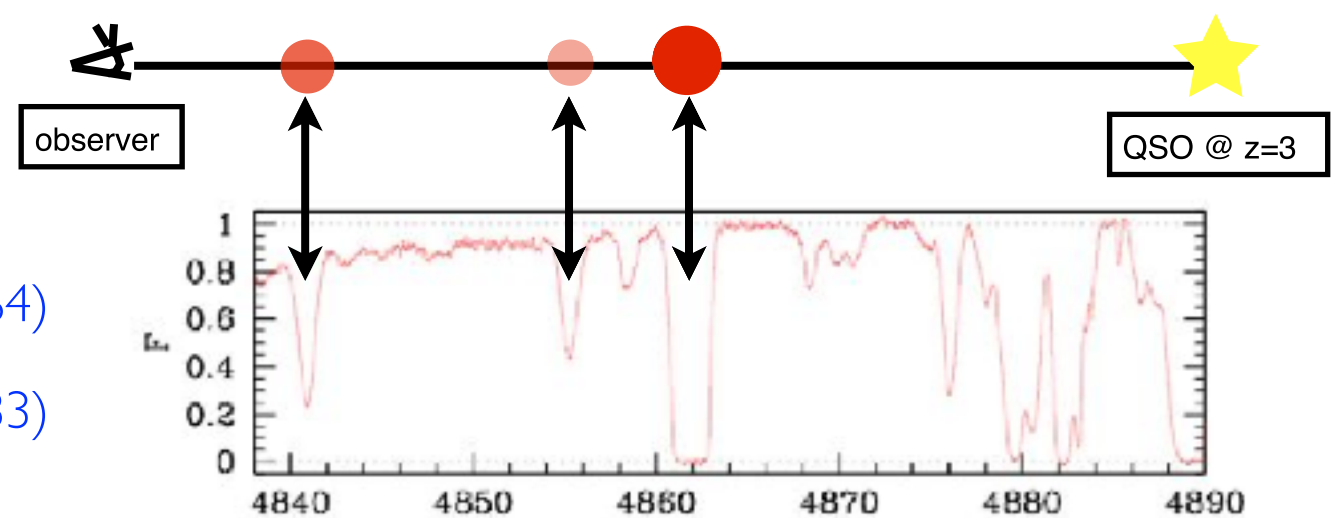
- Ly-alpha forest data constraints:




$m_{\rm WDM} > 5.3\ {\rm keV}$ Iršič et al. (1702.01764)

$m_{\rm FDM} > 10^{-21}\ {\rm eV}$ Iršič et al. (1703.04683)

Cartoon by A. Kamada

# LATE DECAYING DM

Peter1001.3870

Ly-alpha forest data: at z~3

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Simple-minded solution:

- ➔ DM is CDM-like until z~3,
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N-body Simulation (without baryons) says:

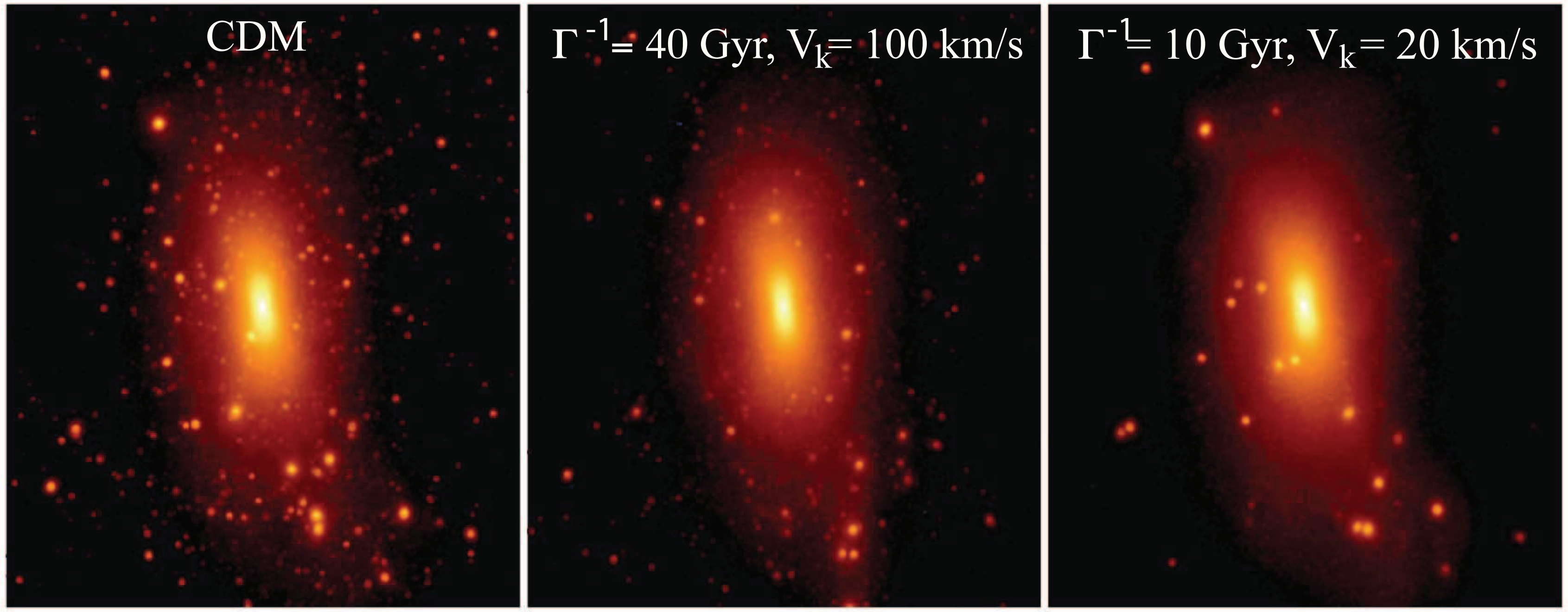
$$\tau_{\rm DDM} \sim 10\ {\rm Gyr}$$
$$v_{\rm kick} = 20 - 40\ {\rm km/s}$$

Wang et al., 1406.0527

solves the problems.

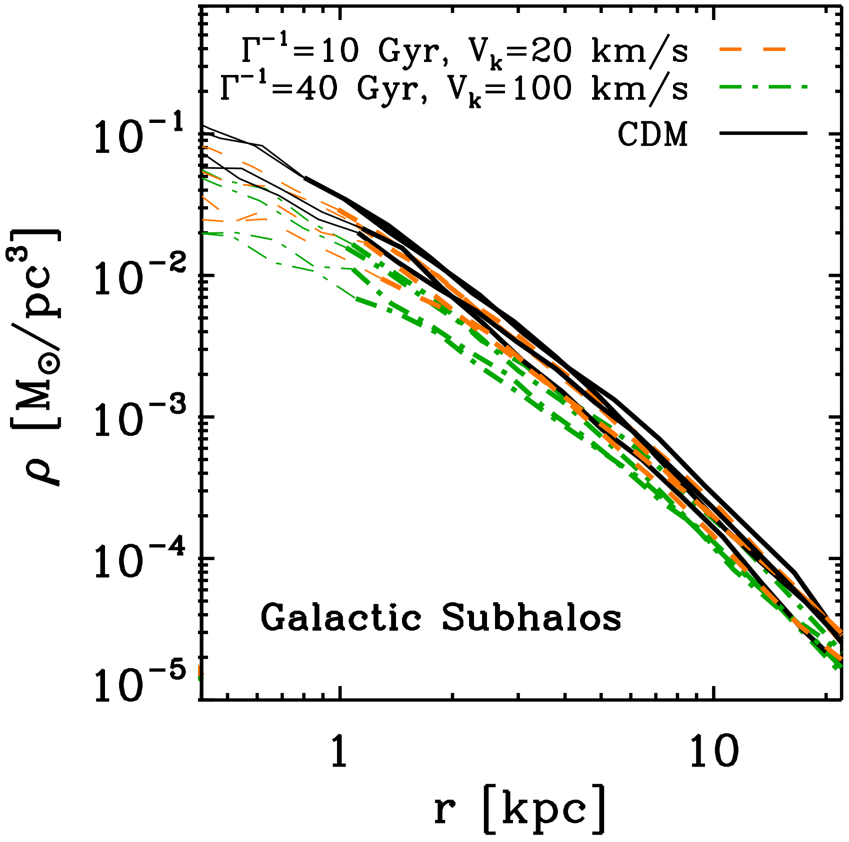
# LATE DECAYING DM

- Solving missing satellite problem: reducing number of subhalos

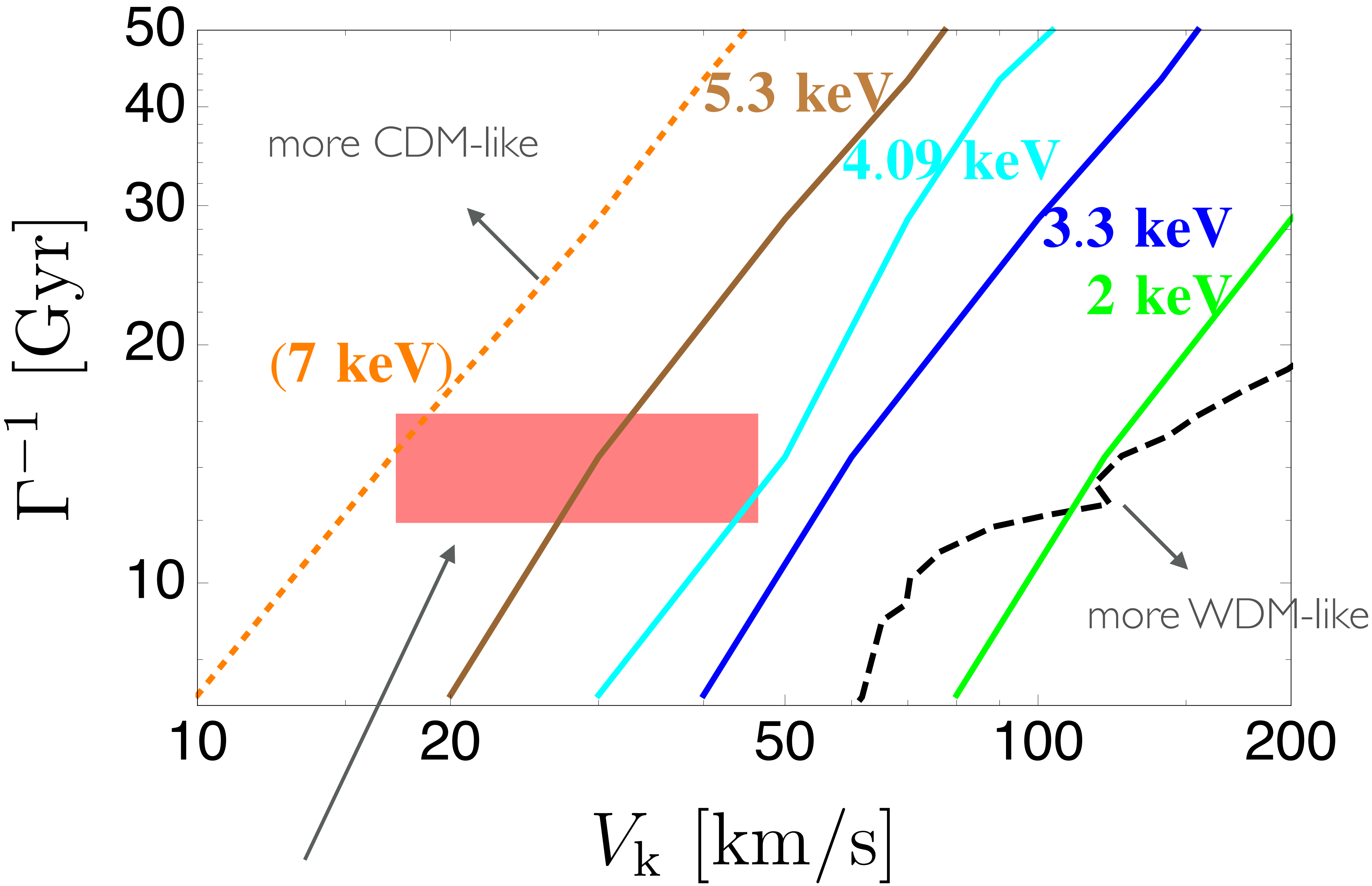



Wang et al., 1406.0527

- Solving too-big-to-fail problem: reducing central densities of subhalos
- Also alleviating Core-Cusp problem:



# DDM: LY-ALPHA FOREST




preferred region to solve
small scale problems

# HOW TO PROBE?

- Lensing can do. Nguyễn, Sehgal, Madhavacheril 1710.03747
- We may need to perform simulation with baryons.

Instead, we can ask

Q1: What particle physics provides DDM scenario?

Q2: What signal can we have?

DDM ⟶ DM + light particle

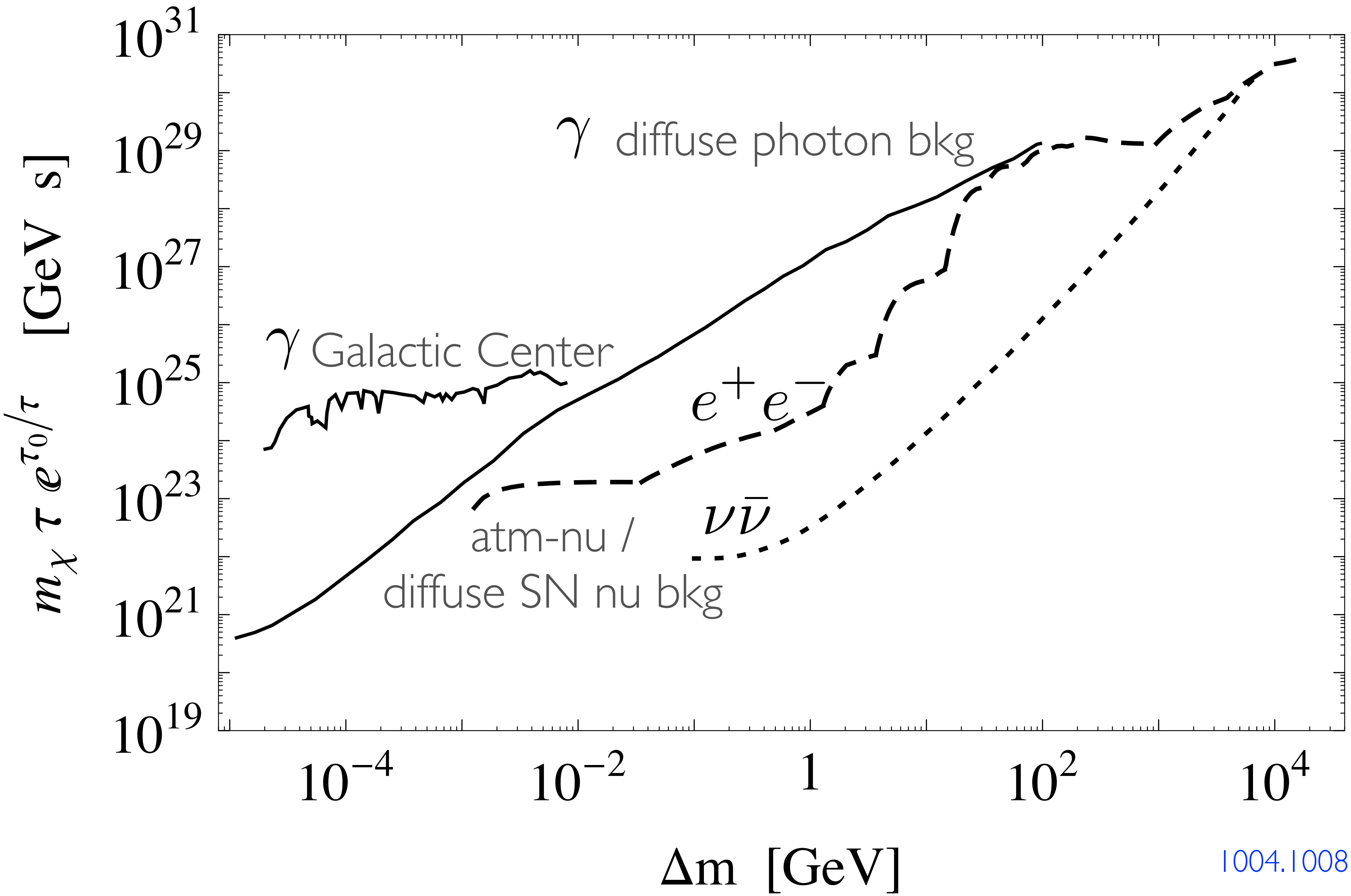
- Good to know

$$\begin{pmatrix} \tau_{\rm DDM} \\ v_{\rm kick} \sim \Delta m/m \end{pmatrix} \Rightarrow \begin{pmatrix} \Phi_{\rm signal} \\ E_{\rm signal} \end{pmatrix}$$

# LIGHT PARTICLE

- Strong constraints for DDM → DM + $e^+e^-/\gamma/\nu\bar{\nu}$

Yuksel, Kistler 0711.2906
Bell, Galea, Petraki 1004.1008




1004.1008

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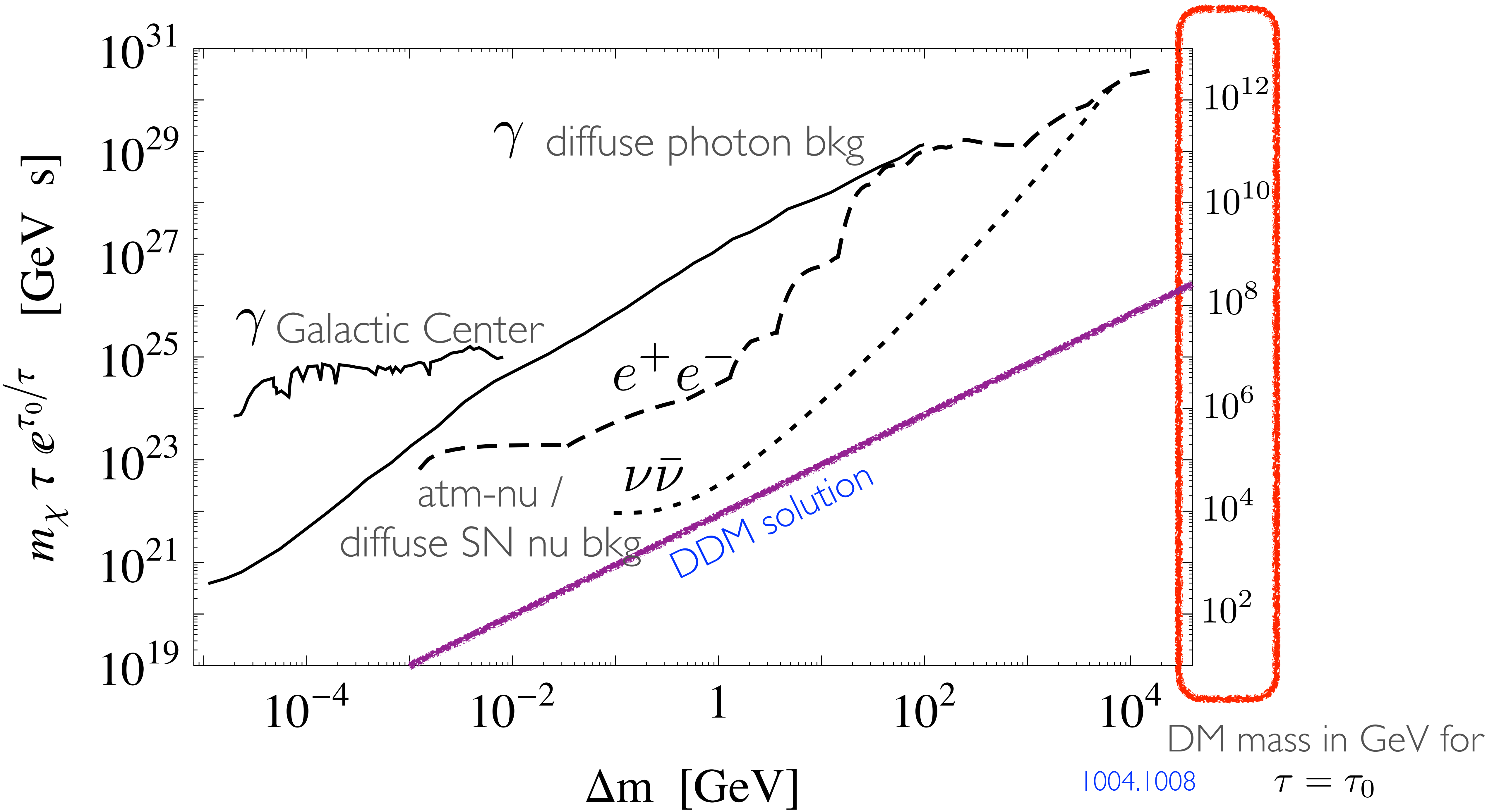


Q: What is viable light particle?

# AXION(-LIKE) PARTICLE

DDM ⟶ Stable DM + light particle

↖ Should not be EM charged & neutrino

- Axion-like particle: very weakly interacting ($\sim 1/f$, $f > 10^9$ GeV), well-motivated.
- But induces a visible signal: ALP-photon conversion under magnetic field
- In our galaxy: galactic magnetic field expected, ~few μG
- Photon with E~Δm, signal morphology depends on magnetic field profile

# AXINO(-LIKE) PARTICLE

DDM → Stable DM + Non-interacting light particle

↑ ALPino ↑ Gravitino ↑ ALP

- Easy to construct in Supersymmetric models
- Good to predict the DDM relic abundance
- Plausible explanation for mass degeneracy of DDM and DM

  Axino mass generated by SUSY breaking, $\sim m_{3/2}$

# MASS DEGENERACY

- In SUSY limit, ALP multiplet is massless by shift symmetry.
- SUSY breaking generates ALPino mass: SUGRA says ~$m_{3/2}$

Goto, Yamaguchi; Chun, Kim, Nilles; Chun, Lukas

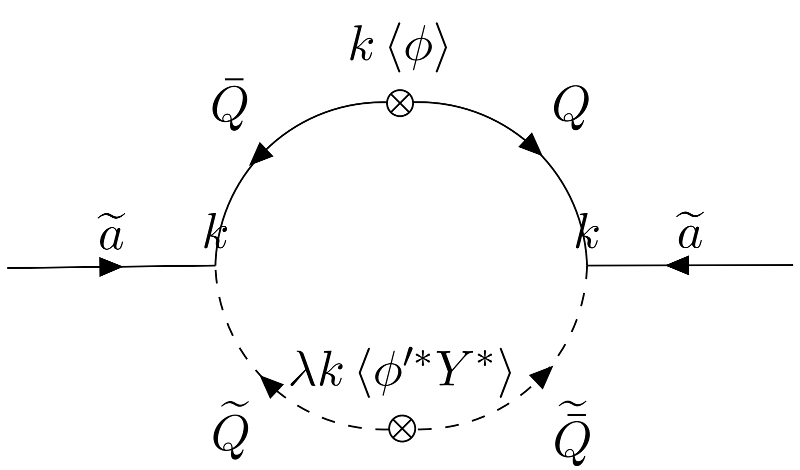
In a simple example,

$$K = |z|^2 + |\phi|^2 + |\phi'|^2 + |Y|^2$$
$$g\left(\phi,\, \phi',\, Y\right) = \lambda\left(\phi\phi' - f^2\right) Y$$
$$G = K + \ln\left|h\left(z\right) + g\left(\phi,\, \phi',\, Y\right)\right|^2$$

$\rightarrow$

$$M_{AA} = m_{3/2}\left\{1 + \mathcal{O}\left(\frac{|\omega|^2}{\lambda^2 f^2}\right)\right\}.$$

- Loop correction,




$$|m_{\tilde{a},\mathrm{loop}}| \sim \frac{k^2}{(4\pi)^2}\frac{\lambda k\,|\langle\phi'^* Y^*\rangle|}{k\langle\phi\rangle} \sim \frac{k^2}{(4\pi)^2} m_{3/2}.$$

k~0.1 $\rightarrow$ $(\Delta m/m \sim 10^{-4})$

# INTERACTIONS

- Consider an effective Lagrangian,

U(1)Y SU(N)h

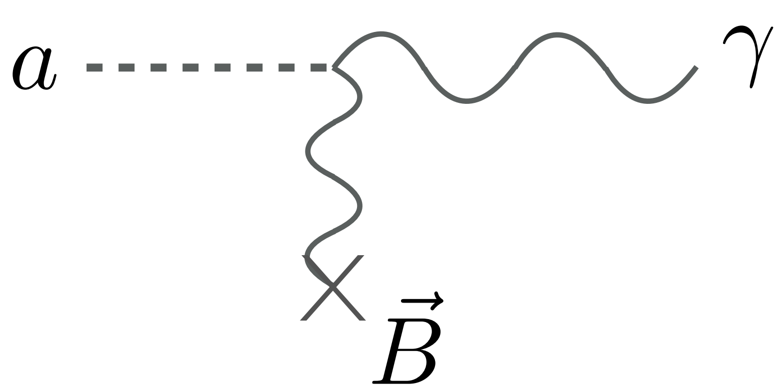
$$W_{\rm eff} \;=\; -\sqrt{2} g_{aB}\, A\, W_B W_B - \sqrt{2} g_{a g_{\rm h}}\, A\, W^a_{\rm h} W^a_{\rm h}\,,$$

for ALPino production, ALP-photon conversion

for ALP mass generation

$$\rightarrow \quad \mathcal{L}_{\rm eff} \;\supset\; g_{a\gamma}\, a\, F_{\mu\nu} \widetilde{F}^{\mu\nu}$$

$$m_a \;\sim\; \Lambda_{\rm h}^2 / f$$



# MASS SCALE

- ALPino-Gravitino interaction,

$$\mathcal{L}_{3/2} = -\frac{1}{2M_{\rm pl}}\partial_\nu a\,\bar\psi_\mu\,\gamma^\nu\gamma^\mu i\gamma_5\,\tilde a\,,$$

$$\rightarrow \quad \Gamma_{\tilde a}^{-1} = \frac{96\pi m_{3/2}^2 M_{\rm pl}^2}{m_{\tilde a}^5}\left(1-\frac{m_{3/2}}{m_{\tilde a}}\right)^{-2}\left(1-\frac{m_{3/2}^2}{m_{\tilde a}^2}\right)^{-3}$$

$$\simeq 10\,{\rm Gyr}\left(\frac{700\,{\rm TeV}}{m}\right)^3\left(\frac{20\,{\rm km/s}}{V_{\rm k}}\right)^5 .$$

- For a successful DDM scenario, $\Gamma^{-1}\sim 10$ Gyr, $V_k\sim 20\text{-}40$ km/s, sub-PeV scale is required.

# ALPINO RELIC ABUNDANCE

- Main production

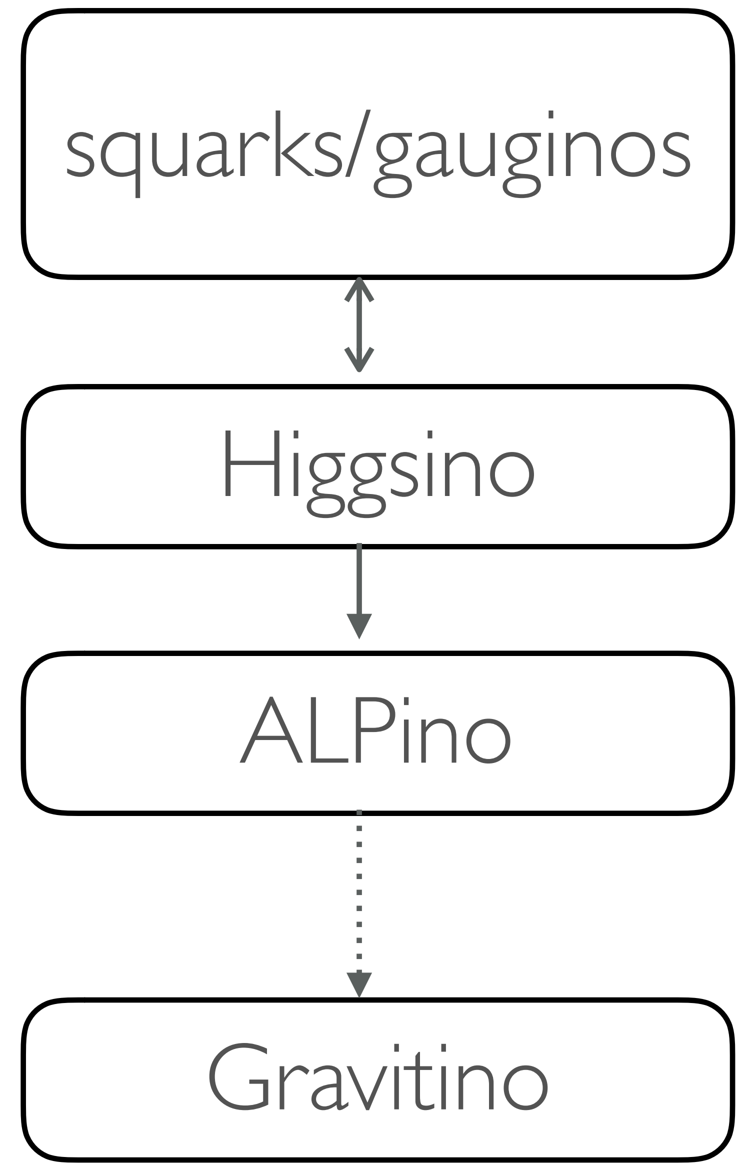
  Freeze-out of Lightest
  MSSM particle, e.g. higgsino

$$\mathcal{L}_{\rm eff} \supset g_{a\gamma}\, a\, F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

→ Decay to ALPino

$$Y_{\tilde{a}} \simeq Y^{\rm fo}_{\rm losp} \times \frac{4+p}{1+p}\left[\frac{g_*(T_{\rm R})}{g_*(T_{\rm fo})}\right]^{1/2}\left(\frac{T_{\rm R}}{T_{\rm fo}}\right)^3,$$

$$Y^{\rm fo}_{\rm losp} = 4\times 10^{-13}\,(m_{\rm losp}/1\,{\rm TeV})$$




- Low reheat temperature is required, $T_R$~500 GeV, i.e., ALPino production ***during reheating***

# Signal of ALPino decay

# ALP-PHOTON CONVERSION

- Under magnetic field, ALP is converted to photon.

$$\mathcal{L}_{\rm eff} \supset g_{a\gamma}\, a\, F_{\mu\nu} \widetilde{F}^{\mu\nu}$$

Eq. of motion →

$$\left(E_\gamma + i\partial_z + \begin{pmatrix} \Delta_e & \Delta_{\rm B} \\ \Delta_{\rm B} & \Delta_a \end{pmatrix}\right) \begin{pmatrix} A_{\shortparallel}(z) \\ a(z) \end{pmatrix} = 0\,,$$

$$\Delta_e \approx -\frac{\omega_{\rm p}^2}{2E_\gamma}\,,\quad \omega_{\rm p}^2 = \frac{4\pi\alpha_{\rm em} n_e}{m_e}\,,$$

$$\Delta_a = -\frac{m_a^2}{2E_\gamma}\,,\quad \Delta_{\rm B} = \frac{g_{a\gamma} B_{\rm T}}{2}\,,$$

Conv. Prob. (for homogeneous magnetic field)

→
$$P_{a\gamma}(s,\Omega) \simeq 2\times 10^{-7} \left|\frac{B_T(s,\Omega)}{\mu{\rm G}}\right|^2 \left(\frac{10^{-8}\,{\rm eV}}{m_a}\right)^4 \times \left(\frac{g_{a\gamma}}{10^{-13}\,{\rm GeV}^{-1}}\right)^2 \left(\frac{E_\gamma}{47\,{\rm GeV}}\right)^2\,,$$

* QCD axion

$$g_{a\gamma} \simeq 0.4 * 10^{-15}\ {\rm GeV}^{-1} \times \left(\frac{m_a}{10^{-6}\ {\rm eV}}\right)$$

Photon flux

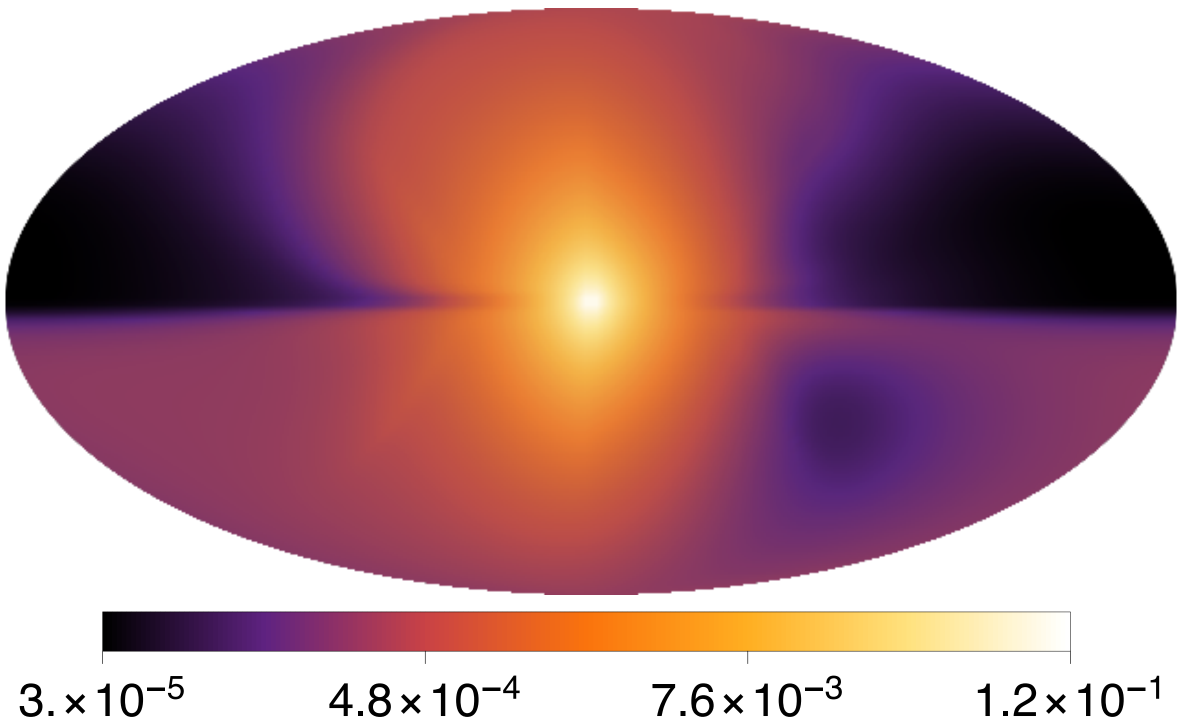
$$E_\gamma^2 \frac{d^2\Phi_\gamma^a}{dE_\gamma d\Omega} \simeq 6\times 10^3\, J_{\rm D,ROI}\, e^{-\Gamma_{\tilde a} T_0}\, {\rm MeV/cm^2/s/sr} \times \left(\frac{E_\gamma}{47\,{\rm GeV}}\right)^2 \left(\frac{700\,{\rm TeV}}{m_{\tilde a}}\right) \left(\frac{\Gamma_{\tilde a}}{10\,{\rm Gyr}}\right) \times \left(\frac{1\,{\rm GeV}}{\Delta E}\right) \left(\frac{1\,{\rm sr}}{\Delta\Omega_{\rm ROI}}\right)\,,$$

$$J_{\rm D,ROI} \simeq 22 \times P_{a\gamma}$$

Fermi-LAT (observed):

$$E_\gamma^2 \frac{d^2\Phi_\gamma^{\rm obs}}{dE_\gamma d\Omega} \simeq 6\times 10^{-4}\,{\rm MeV/cm^2/s/sr}\,,$$

# SIGNAL MORPHOLOGY




Our scenario

$E_\gamma = 47\,\mathrm{GeV}$ $g_{a\gamma} = 10^{-13}\,\mathrm{GeV}^{-1}$

$\tau_{\tilde{a}} \sim 3 \times 10^{17}$ s $m_a = 10^{-8}\,\mathrm{eV}$

Magnetic field profile from Jansson & Farrar, *Astrophys. J.*, vol. 757, p. 14, 2012

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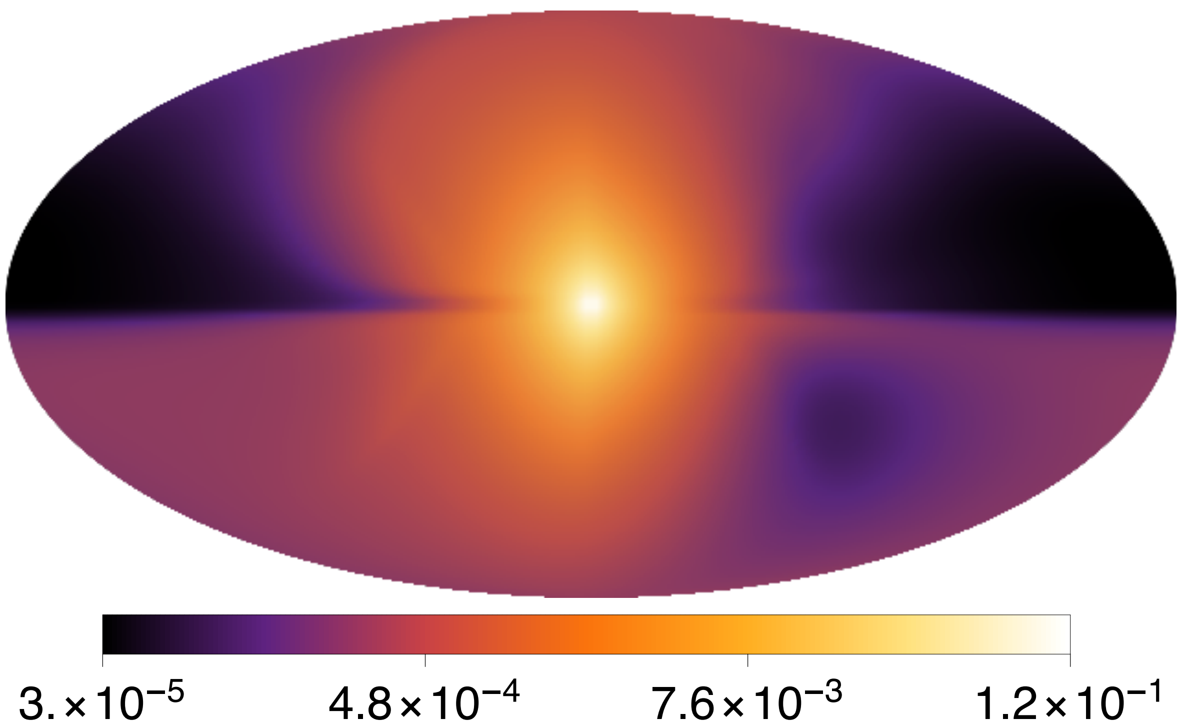


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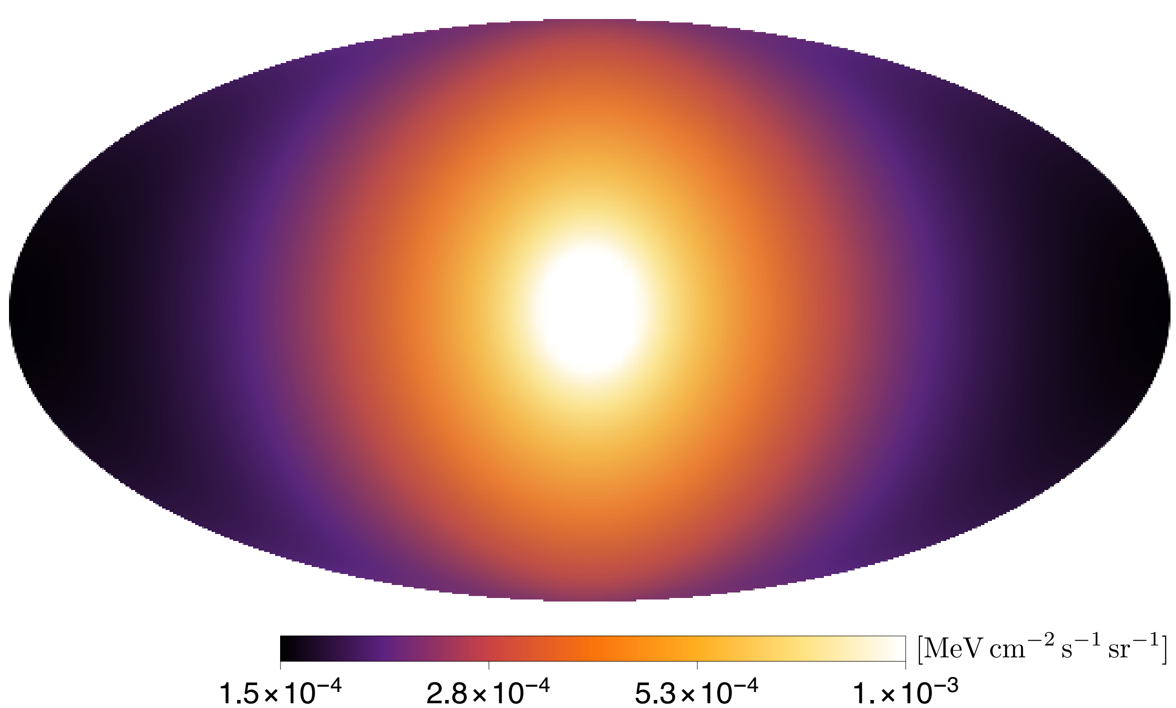


Meta-stable DM decay to diphoton

$E_\gamma = 47\,\mathrm{GeV}$ $m_{\mathrm{DM}} = 94\,\mathrm{GeV}$

$\tau_{\mathrm{DM}} \simeq 10^{28}\,\mathrm{s}$.

# CONCLUSION

- Cold dark matter (CDM) is successful to explain current universe.
- Shortcomings arise at small scale structure, <O(100) kpc.
- *Decaying dark matter* (tau~10 Gyr, $V_k$~30 km/s) is a good & interesting alternative.
- Axino-like particle ⟶ Axion-like particle + Gravitino provide a good decaying dark matter scenario.
- ALP-photon conversion produces distinct signal; morphology, energy scale.
- Gravitational probes are also important in future research.